CONSTRAINTS ON GALAXY FORMATION THEORIES

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Abstract

The present theories of galaxy formation are reviewed. The relation between peculiar velocities, temperature fluctuations of the microwave background and the correlation function of galaxies point to the possibility that galaxies do not form uniformly everywhere. The velocity data provide strong constraints on the theories even in the case when light does not follow mass of the universe.

1. Initial Conditions

The universe contains a wide dynamic range of objects : from stars ($1 \ M_\odot$) all the way to superclusters ($10^{16} \ M_\odot$). A major question that we are unable to answer yet is whether the formation of structure has started with smaller masses clustering on ever larger scales[1], or whether extremely large structures formed first, then subsequently fragmented into smaller ones[2]. If we knew the precise initial conditions then the present structure of the universe could be derived by applying the laws of physics. Let us summarize, what has to be known about the initial conditions for this ambitious project.

The fluctuations are likely to be adiabatic, since the specific entropy of the universe, n_B/n_γ is tied to microscopic parameters of particle physics. Entropy fluctuations, once popular, can be generated by huge amounts of shear, e.g. In the inflationary theories quantum fluctuations arise in a natural way. However, the necessary amplitude seems to require rather special prescriptions for the effective potential[3].

The initial perturbations are expected to be scale free, therefore their Fourier amplitude depending on the wavenumber k can be well described by a power law, $|\delta_k|^2 \propto k^n$. If the spectral index is $n = 1$, the amplitude of the different perturbations is the same when their wavelength equals the horizon size. This 'double scale-invariant' is called the Zeldovich spectrum, and is known to arise in inflationary scenarios[4].

There are severe constraints on the fluctuation amplitudes. If the fluctuations were adiabatic, the perturbations of the metrics generate fluctuations in the temperature of the microwave background. On small angular scales (4.5 arc mins) these limits are extremely small[5]:$\Delta T/T < 2.9 \times 10^{-5}$. The H-He plasma becomes gravitationally unstable only after recombination, at $Z \sim 1000$. At this point the density and temperature fluctuations are similar, $3\ \Delta T/T = \Delta\rho/\rho$. Since the standard growth of fluctuations in a flat universe is $(1 + Z)^{-1}$, this does not leave enough margin for fluctuation growth, the fluctuations cannot reach the nonlinear stage our universe seems to be in today. Present calculations confirm[6] that if the universe is baryon dominated, only prohibitively high initial fluctuation amplitudes can result in the formation of galaxies. If the universe is dominated by some form of collisionless dark matter, the dark matter fluctuations are unaffected by pressure, therefore grow even before recombination. After recombination these curvature perturbations caused by the dark matter will accelerate fluctuation growth in the baryons, so the $\Delta T/T$ constraints are less stringent.

Though the initial spectrum is a power law, by the time it becomes nonlinear it will be considerably modified. When the universe is radiation-dominated, fluctuations within the horizon have a minimal increase[7], whereas the ones outside the horizon grow. This effect will bend the slope of the spectrum from n to $n - 4$ for

wavenumbers higher than k_{eq}, corresponding to the size of the horizon when the matter and radiation energy densities were equal. The presence of the collisionless dark matter results in distortions of a different kind: the free motion of particles erases structures smaller than the free streaming scale[8,9,10,11]. The mass scale of this collisionless damping process can be expressed in terms of the mass and entropy of the particles the dark matter consists of. $M_x \approx 2.2\ m_p^3 m_x^{-2}$. In the case of neutrinos this mass takes the value of $M_{\nu m} = 3.2 \times 10^{15} m_{30}^{-2}$ $M_\odot$, corresponding to the comoving length scale $\lambda_{\nu m} = 41\ m_{30}^{-1}$ Mpc. Depending on what the 'temperature' of the dark matter is, this damping scale can change from the above 41 Mpc to extremely small values. The neutrinos are *hot* particles, since their average momentum is close to that of the background radiation photons. Most other candidates for the dark matter like axions and photinos - yet undiscovered - would have decoupled much before the neutrinos, having a lower entropy or temperature, so they are called *cold*. They hardly move at all, their damping scale is negligible. Intermediate candidates, like a gravitino of 1 keV mass would be *warm*.

A major underlying assumption in calculating most consequences of a given fluctuation spectrum is that the phases of the individual Fourier components are random, ie. the perturbations are a random Gaussian process. One can envisage scenarios, where this will not be the case, like perturbations originating from strings[12]. For a given spectrum combined with the assumption of random phases one can calculate the distribution of mass fluctuations, density of local peaks, density profiles around local peaks, the distribution of peaks of a given size, etc.

The expansion of the universe is characterized by three quantities: $\Omega = \rho/\rho_{crit}$, the density parameter, H_0, the Hubble constant, Λ_0, the cosmological constant. If $\Lambda_0 = 0$ and $\Omega = 1$ the universe is flat, which appears to be necessary for inflation. Λ_0 is generally assumed to be negligible. Calculations of the primordial ^{4}He and

$D+^3He$ abundance indicate[13], that the baryon density of the universe at the time of primordial nucleosynthesis lies in the range of $0.01 < \Omega_B < 0.1$. This suggests that if baryons dominate the mass density then the universe is open by a large margin.

Fluctuation growth also depends on the density of the universe. If $\Omega < 1$, the growth of perturbations effectively stops at the redshift $Z = \Omega^{-1}$. The detailed predictions of $\Delta T/T$ are just below the current limits if the dark matter consists of neutrinos with about 30 eV mass, and restrict Ω if the cold particles dominate the universe [6]: $\Omega \geq 0.2 \times h^{-4/3}$ where $H_0 = 100h$ km /s Mpc. In deriving this limit it was assumed that galaxies follow the mass distribution: the amplitude of the fluctuations today was normalized to J_3, the integral of the galaxy-galaxy correlation function $\xi_g(r)$.

2. Nonlinear structure

Here we would like discuss the expected structure of the universe if the dark matter is either hot, warm or cold. Once the first mass scale in a spectrum with a large damping cutoff (hot) reaches nonlinearity, particle trajectories cease expanding away from each other and converge, resulting in the temporary formation of caustics. The density becomes very high and a flat 'pancake' is formed[2]. At first they arise at isolated spots where the initial velocity perturbations had the largest gradient. Soon these regions grow, turning into huge surfaces which intersect, forming the walls of a cell-structure which is itself gravitationally unstable. The methods of catastrophe theory were applied[14] to analyze structure that develops in such potential motion. It was found that the two dimensional pancakes are only the lowest order singularities; other singular topological structures should also appear. String-like features are one example, and they can be seen in the N-body simulations.

When the intersection of trajectories takes place, gas pressure builds up, the velocity of the collapsing gas exceeds the sound speed and a shock wave is formed[2]. The gas is shock-heated up to keV temperatures and cools by emitting radiation over a broad spectrum. The UV and soft X-ray emission can photoionize the intergalactic medium, making galaxy formation in regions that have not yet formed pancakes more difficult, which would accentuate the contrast in galaxy density between the strings and pancakes vs. voids, even though the density contrast may be only 3-10.

If the dark matter is cold, then the mass autocorrelations are logarithmically divergent towards the smallest scales. These objects will collapse first, the scales determined by the baryon Jeans mass at around recombination. Collapse of larger scale systems follows subsequently. It is believed that the statistical properties on a given mass scale can be reasonably well understood by studying the Gaussian random fluctuations obtained by filtering out all the smaller scale contributions from the power spectrum. Recently as major effort has been undertaken[15], where galaxies were associated with peaks of a given height of the random fluctuation field and various properties like correlation functions, mean shapes, densities etc were calculated in a manner similar to previous work on pancakes[16]. If the dark matter is warm, it will still form pancakes, though of galactic size. There the cooling is much more efficient[17], those timescales will determine the fate of each object.

In either of the above scenarios it seems to be very hard to avoid strong initial explosions and rapidly cooling shocks, which compress the gas and provide seeds for the next generation of explosions, as suggested by Ostriker and Cowie [18]. The complicated nature of such calculations has yet prevented a very detailed discussion, but the importance of these processes is unquestionable.

3. Peculiar velocities

If we knew all the parameters listed above, it would be relatively easy to follow the evolution of the universe. Only gravitational forces act on collisonless dark matter so one can numerically solve the transport equations, even in the nonlinear regime. This has indeed been done, as we discuss here. Given the initial conditions, these numerical experiments can tell us the mass distribution in the universe. One can hope, that the structure obtained this way will resemble the real universe, ie. galaxies trace the mass distribution.

Starting from the above mentioned initial conditions extensive N-body simulations [19,20] were made. The free parameters of the calculations are Ω, H_0 and the initial amplitude of the fluctuations. For a given Ω one can use conservative limits for the age of the universe to obtain a value of H_0. If $\Omega = 1$, then $t_0 > 12$ Gy requires $H_0 < 54$ km/s Mpc. The initial amplitude can be defined in various ways. For simulations with hot dark matter the epoch of galaxy formation Z_{GF} was the redshift when 1 percent of all particles have gone through a 'caustic'. For cold dark matter, due to the growth of nonlinearity, $\xi(r)$ is rapidly increasing both in slope and amplitude, just like for hot dark matter. One can define *today* when the correlation function of the particles most resembles that of the galaxies, ie. a power law with a slope -1.8.

$$\xi(r) = (r/r_0)^{-1.8}$$

The simulations have encountered a major difficulty : the random velocity dispersion of galaxies is well known[21]:

$$< v_{12}^2 >^{1/2} \approx 300 - 400 \text{km/s}.$$

Both in the neutrino and cold dark matter simulations, when the density correlations are just about right, velocity dispersions are in the 1200 km/s range, clearly too high.

$$< v_{12}^2 >^{1/2} \approx (1200 \text{ km/s}) \ \Omega^{0.6} \xi_0$$

where ξ_0 is the value of the mass autocorrelations at 5 Mpc radius. Comparing this to the data, this suggest that $\Omega \ll 1$, forbidden by the $\Delta T/T$ constraints. Since a low Ω model is ruled out, the only remaining possibility is to have $\xi_0 = |\delta\rho/\rho|^2$ fairly small. Then we are in a sharp contradiction with the observed galaxy autocorrelation.

Here one should note, though, that all calculations so far have assumed, that the distribution of galaxies follows the mass distribution, ie. $\xi_g(r) = \xi_m(r)$. It is $\xi_m(r)$, which determines both the $\Delta T/T$ fluctuations and the peculiar velocities, and it is $\xi_g(r)$ that we can observe. Since $\xi_g(r)$ seems to be too large to be in agreement with either $\Delta T/T$ or $\langle v_{12}^2 \rangle$, and changing Ω does not resolve the problem, the next possible solution may be that the mass fluctuations are relatively small, whereas $\xi_g(r) \gg \xi_m(r)$. This means, that *galaxies do not form with uniform probability everywhere*, the formation rate is 'biased' towards some regions.

This can be quite natural, though, since galaxies consist mostly of baryonic gas capable of emitting and absorbing radiation. These dissipative processes, strongly density and temperature dependent, occur at a different rate at different places[17]. All these effects, combined with possible shock waves due to the finite pressure in the H-He gas, may have an important role in determining where galaxies form. As a result, the galaxies may not follow the light at all, so the mass autocorrelation should not be compared to the galaxy autocorrelation. Galaxy formation, as long as it is a random process, initiated by gravitational infall will be likely to start at the regions of highest densities. One can therefore associate the particles in these regions with galaxies. This 'biasing' of galaxy formation towards these high densities is a heuristic

procedure, but probably a fair approximation to what really happens. The physical explanation of what the threshold of the selection should be is much less clear, it can only be adjusted to the observed number density of galaxies. This 'biasing' process enhances the correlations, without invoking large peculiar velocities.

If we consider the large scale velocity fields, they provide strong upper limits to the 'biasing' factor[22]. The dispersion of the center-of-mass velocity of a sphere with radius R is given by

$$\langle V^2 \rangle = (\mathrm{H}_0 f)^2 \int_0^\infty dk |\delta_k|^2 W^2(kR)$$

where $f = \Omega^{0.6}$ and $W(kR)$ is the window function, the Fourier transform of the spherical distribution [23]. The window function effectively eliminates contributions from scales smaller than R, so $\langle V^2 \rangle$ is a genuine measure of the large scale fluctuations, which are believed to be still close to linear. During the last few years there were several attempts to determine the peculiar velocities of spheres of galaxies centered around us, although the errors are considerable[24]. The results are not yet conclusive, but potentially they are an important test of the fluctuation amplitude.

Another measure of the large scale structure of the universe is the cluster - cluster correlation function $\xi_{cc}(r)$. It has the same functional form as the galaxy autocorrelation, but the amplitude is considerably larger [25]:

$$\xi_{cc}(r) = (\frac{r}{36\mathrm{Mpc}})^{-1.8}$$

Furthermore, the amplitude is dependent upon the richness class. It has been shown recently, that this richness dependence can be nicely explained, if we assume that the universe has a scale invariant property over the volume of the Abell catalogue. For each cluster sample one can derive the mean distance between clusters ($D = n^{-1/3}$),

which would uniquely characterize the richness. If we measure the length in these units, the richness dependence disappears[26]:

$$\xi_{cc}(r) = 0.35(r/D)^{-1.8}$$

Originally Mandelbrot [27] has suggested such a 'fractal' structure for the universe. The physical meaning of this scale invariance is not absolutely clear. It is unlikely that it could be generated via nonlinear gravitational dynamics, since the corresponding velocities on 40 Mpc scales would be enormous. There are suggestions, that cosmic strings may have such an effect[28], but other explanations attribute the difference in the clustering amplitude to the fraction of galaxies associated with clusters [29].

Recent calculations indicate, that for certain kinds of fluctuation spectra the correlation function of 'biased' regions may be a power law over a wide dynamic range, and the slope of the power law would depend on the threshold set for galaxy formation [30], contrary to previous work, claiming that $\xi(r)$ would be amplified by a constant factor [31].

5. Conclusion

All the present theories of galaxy formation fail to explain the observed universe in its full complication. The recent observations of the microwave background fluctuations provide the strongest constraints on present theories. The details of galaxy correlation properties are a new challenge, indicating that galaxies are unlikely to be tracers of the mass distribution. The peculiar velocity field of galaxies and clusters may provide a way to probe the fluctuations even in this case.

7. References

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